Conceptual Design for a Scintillating-Fiber Neutron Detector for Fusion Reactor Plasma Diagnostics

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A conceptual design for a "pointing" neutron detector that is capable of delivering 10^4 - 10^5 Hz countrate of T(D,n) events from triton burnup at a deuterium-burning tokamak is described. The detector consists of collimated bundles of scintillating fibers that are separated by metal or polyethylene. These bundles in turn are set into a larger collimator that has some of the bundles set in "unplugged" holes and others in "plugged" holes whose countrate difference gives the net countrate. It is computed that the use of a 6 MeV_{ee} (electron equivalent) discriminator will allow 14-MeV neutron countrates of $2x10^4$ Hz in a DD machine or 3 MHz in a DT machine, while effectively rejecting the gamma background. The efficiency-area product for 14-MeV neutrons will be ~ 0.014 cm^2. The angular resolution is computed to be 4.5° HWHM for a 35 cm long collimator.

Introduction

The International Thermonuclear Experimental Reactor (ITER) is a worldwide effort, now in the engineering design stage, to construct a reactor that operates at nearly 100% on the D(T,n) reaction. However, most present tokamaks operate mainly on D(D,n) reactions, with only 0.5% to 2% T(D,n) reactions from triton burnup. We want a 14-MeV neutron detector that operates at 10 to 100 KHz on a DD machine and > 1 MHz on a DT machine. We propose a detector composed of hundreds of small fibers of plastic scintillator, separated by metal, where 14-MeV neutrons will create light pulses that are much larger than individual gamma ray interactions or lower-energy neutron interactions. In our design, collimation will typically allow only 1/10 of the DT neutron flux to reach the detector, which is necessary because we only want to view a small portion of the plasma at a given time. High detector efficiency, however, still allows large count rates to be achieved. For triton burnup applications the total neutron flux on a DD machine includes typically 100 DD neutrons per DT neutron. The gamma ray flux, in turn, is probably ten times the total neutron flux.

Since the development of the plastic scintillation fiber[1], its use has expanded mostly in high energy physics research[2]. The general theory and practice of neutron detection using plastic scintillators[3,4,5] and scintillating fibers[6,7,8,9] is fairly well documented. Our main emphasis in this paper will be on the simulations of detector and collimator performance and the background radiation rejection using the codes MCNP[10] and the code of Cecil, et al.[11].

Neutron Response of Detector

The processes simulated in the code of Ref. 11 are the scattering from protons and carbon nuclei in the scintillator, proton slowing and "punching out" (exiting the fiber), and energy dependent light output. We have considered a monodirectional, monoenergetic flux of neutrons incident on a single fiber and calculated the probability that neutron interactions will lead to an event crossing the discriminator threshold. The angular dependence of this efficiency for incident DD and DT neutrons is given in **Figure 1.** The calculations are normalized to a unit light-producing interaction in the fiber. The signals are produced by recoil protons, where the mean track length of a 14-MeV proton is about 2.5 mm. When the fiber diameter (here 1 mm) is smaller than the range of the proton, the largest pulse heights are preferentially produced by on-axis neutrons that scatter at an angle near 180°. If the incoming neutrons enter at an angle off-axis, the efficiency drops because the recoil proton has an increased probability of punching out through the side of the fiber. The signals from DD neutrons, with their short proton track length, are little affected by incident angle. Extrapolating from measured light yields in 1 mm fibers[2] and assuming a 25% photcathode efficiency, using Poisson statistics we calculate a pulse height resolution of 10% for typical 14-MeV neutron events.

The conceptual design of a detector is shown in **Figure 2**. The fibers are set into a block of aluminum. The uncollided DT neutrons arrive axially. All the fibers butt up against a single tube, with a single channel of electronics. Proton crossing is disallowed by the metal between the fibers so that full pulse height will be realized only for those events where the scattering angle is fairly near 180°. The metal between the fibers will also stop Compton electrons or at least decrease their energy greatly. The segmentation of the scintillator volume into fibers will lead to much greater sensitivity to neutrons (which produce recoil protons) than to gamma rays (which produce recoil electrons with long path lengths). In this design the fiber bundles are 1.75 cm in radius, containing 91 fibers of 1 mm in diameter with a pitch of 1.5 mm. The bundles are 10 cm long. There are six bundles in the collimator, arranged in a circular configuration. The collimator is 9.1 cm in radius and 35 cm long. Of the six holes for collimation, three are plugged with polyethylene. There are six phototubes. The discriminator output for the three that have holes are fanned-in together and the three that have plugs are fanned-in together. It is the *difference* between these two discriminator-crossing rates that is the net count rate. The gain matching between tubes will have to be better than ±10%.

In MCNP, a source at nominally 200 cm was moved it back and forth horizontally, resulting in a calculation of the efficiency-area product versus angle. Included in the calculation is the effect of the angular-dependence of the probability that the signal will cross a 6 MeV_{ee} discriminator, as taken from **Figure 1.** The angular efficiency functions, shown in **Figure 3**, cancel each other out almost perfectly at angles greater than 10°, giving a net angular resolution is 4.5° HWHM. Such an angle provides resolution of ~10% of the minor radius of the tokamak. Also shown is the case of the bare detector, minus collimator. The angular dependence to the response is a combination of the proton punch-through effects[6] and angular-dependent detector self-shielding. The directionality of the fibers allows use of a much more compact collimator to achieve spatial resolution of the neutron emission profile.

Gamma Response of Detector

Using MCNP in photon-electron mode we calculated the response of the detector to gamma rays of 60 KeV, 662 KeV, 1.25 MeV and 2.75 MeV. For comparison, a second set of calculations was performed on a bare rod of scintillator material, 10 cm in length, having the same volume as the combined volume of the fibers. Each spectra is dominated by the Compton interaction. At the lowest energy, the mean pulse height in either detector is ~89% of the gamma energy. Otherwise, for the rod the mean pulse height is ~42% of the gamma ray energy. For the fiber bundle, it is less than 20% of the gamma energy. The detection efficiency increases slightly versus the bare rod for the higher-energy sources because the presence of the aluminum and the collimator.

As discussed before, the detector sits near the tokamak and sees a flux of uncollided 14-MeV neutrons from the region of interest in the plasma, but it is submerged in a nearly isotropic gamma flux φ_γ of 10^4 larger. We simulated the interaction of the detector with this gamma ray flux using MCNP. The source is a spherical shell that encloses the detector. The source energy spectrum used for the calculations is flat from 0 to 1 MeV, tapering off linearly to zero intensity at 3 MeV. The mean energy is 1.1 MeV. **Figure 4** shows the single-interaction pulse height spectra calculated with MCNP for these same two detectors. As expected, the effect of using the fibers instead of the bare rod is to force the distribution to a lower mean pulse height. The pulse-height distribution in the fiber detector given roughly as a negative exponential with a mean value α = 0.17 MeV_{ee}. From varying the fiber diameter and the energy spectrum, it was found that the mean pulse height is proportional to fiber diameter and is independent of the form assumed for the high energy tail of the gamma ray spectrum. This is because most pulses are from Compton electrons that traverse one fiber, with an mean chord length equal to the diameter.

Background Rejection vs. Threshold

A pileup simulation was performed using the negative exponential functional form for the gamma ray singles spectra. Here, the resolving time of the detector is taken to be a typical pulse width of τ = 5 ns, and the rate of gamma ray interactions is $r = \varphi_\gamma (\varepsilon A)_{\gamma 0}$, where $(\varepsilon A)_{\gamma 0}$ is the efficiency-area product for gamma rays at zero discriminator threshold. First, the pulse height distribution for n gamma rays interacting simultaneously is taken as the (n-1)-fold convolution of the singles pulse height spectrum. A Poisson distribution for the number of interactions occurring simultaneously in the detector is taken, where the average value of the distribution is $r\tau$. Finally, the distribution is summed over all possible numbers of simultaneous interactions. The resulting pileup pulse height distribution is:

(1) $$S(h) = \sum_{n=1}^{\infty} \frac{(r\tau)^n e^{-r\tau} h^{n-1} e^{-h/\alpha}}{n!\,(n-1)!\,\alpha^n}$$

This function is approximated as a gaussian with $\sigma = \alpha\sqrt{2r\tau}$ (to within 20% accuracy for our purposes) for $r\tau > 20$. Estimates of detector counting rate and background versus discriminator level were made using this approximation. Background DT and DD neutron radiation was found to not contribute significantly to pileup under our assumptions. The rate at which the discriminator, set at a threshold H, will trigger from gamma pileup is given by:

(2) $$R_B = \frac{1}{\tau}\ \mathrm{erfc}\left(\frac{H/\alpha}{\sqrt{2r\tau}}\right),$$

which is proportional to the area under the gaussian curve above the threshold. The rate of gamma events is not independent of the neutron counting rate, rather it given as:

(3) $$r = \frac{10^4 R_n}{\varepsilon'(H)} \frac{(\varepsilon A)_{\gamma 0}}{(\varepsilon A)_{n0}}$$

where R_n is the counting rate of 14-MeV neutrons above the threshold H, $\varepsilon'(H)$ is the relative efficiency for firing the discriminator by an interacting 14-MeV neutron (as given in **Figure 1**), and $(\varepsilon A)_{\gamma 0}$ and $(\varepsilon A)_{n0}$ are the efficiency-area products for the interaction of gamma rays and 14-MeV neutrons in the detector, respectively (with a zero discriminator setting). The factor of 10^4 is to account for our conservative assumption that there are 10 total DT neutrons per DT neutron in the detector's field of view, 100 DD neutrons per DT neutron, and 10 gamma rays per DD neutron. The detector is the 1 mm fiber bundle, $(\varepsilon A)_{\gamma 0} = 0.65\ cm^2$, $(\varepsilon A)_{n0} = 0.18\ cm^2$. The ratio R_n/R_B is extremely sensitive to the counting rate and very sensitive to the assumptions about the ratio of the background gamma ray flux to the source neutron strength. If we fix R_n/R_B at 100, the solution of (2) and (3) simultaneously gives a maximum DT countrate of about 2.5×10^4 Hz in triton burnup mode. For a tritium-burning tokamak, the corresponding countrate is 3×10^6 Hz.

Conclusions

The detector will have a sum of 1000 net counts every 40 msec, which should be good for temporal/spatial triton burnup measurements. The electronics will be very simple and the detector and collimator promise to be lightweight and portable. Prototype testing has been performed over the last year, and is discussed in a companion paper at this conference. At a tritium-burning machine, such as ITER, the same detector can be used at much higher countrates because the gamma flux is relatively much smaller. Radiation damage would limit the amount of time a fiber detector could be placed near the reactor. Other segmented detectors, such as long, thin ionization chambers can provide similar directional effects.

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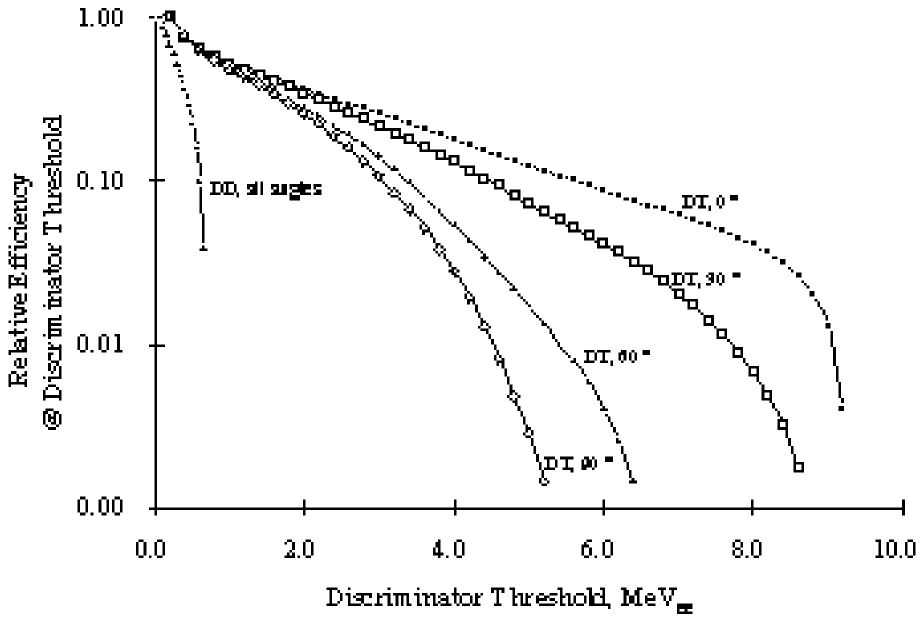
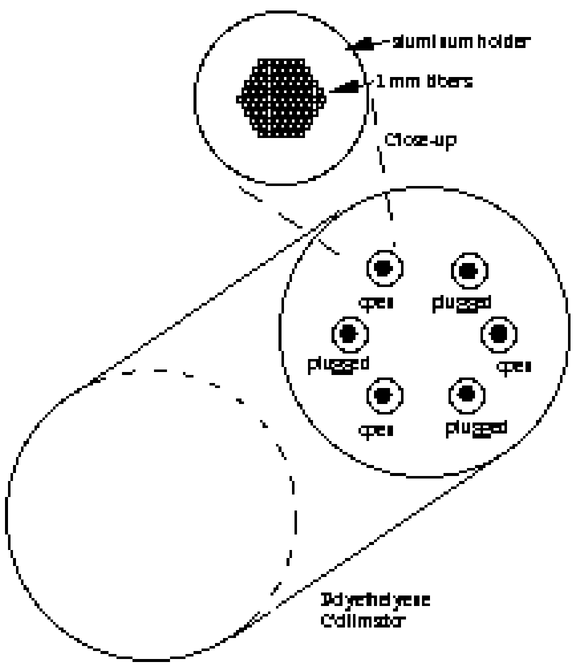
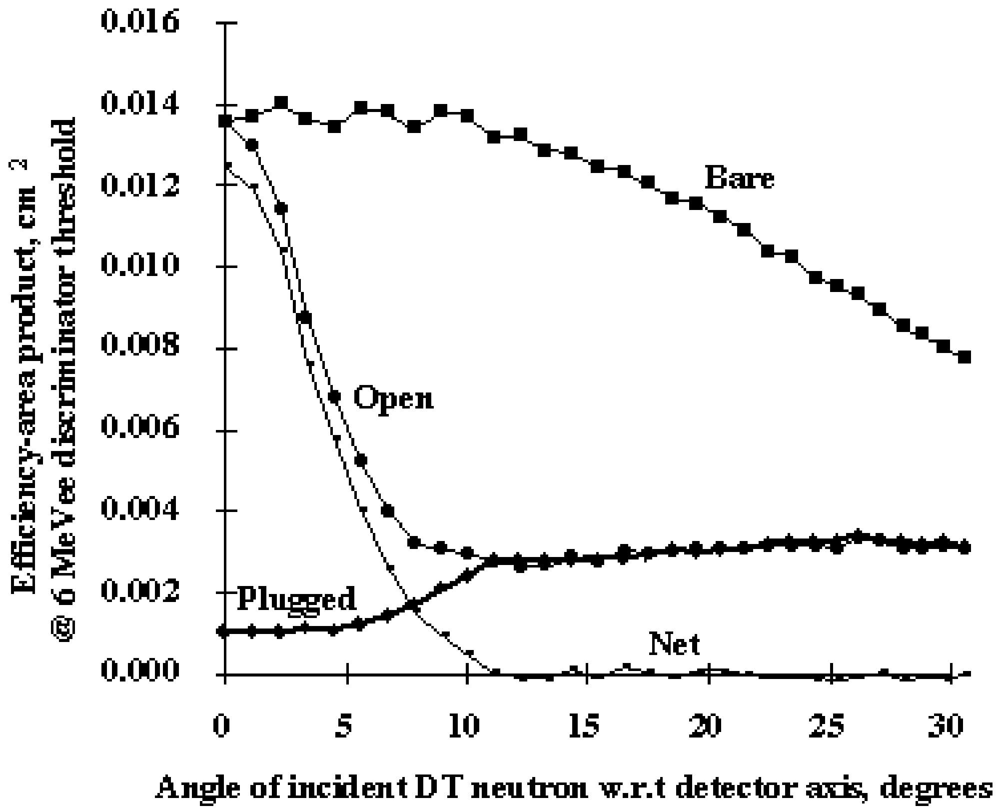


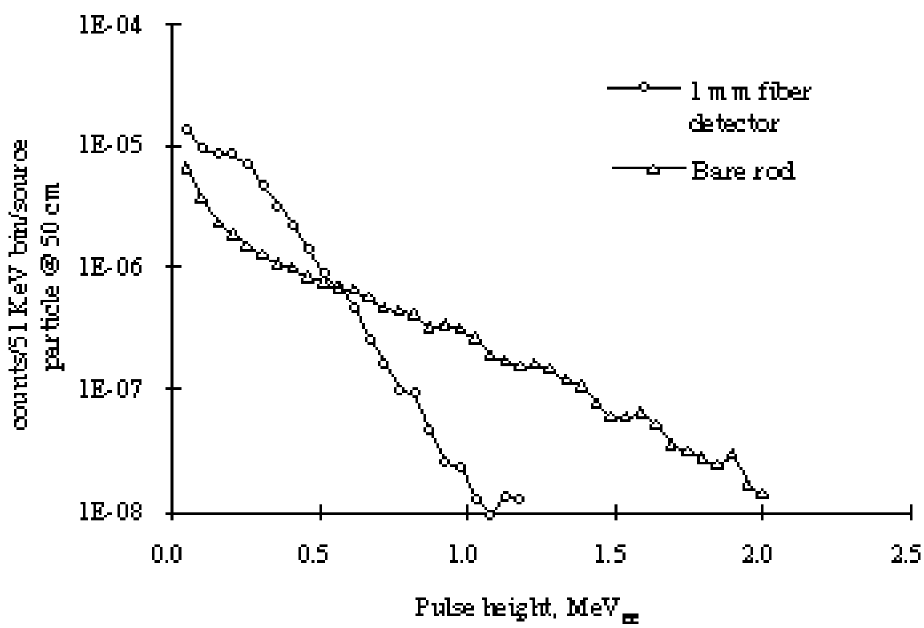
1. Probability that a light-producing event in a scintillating fiber will cross a given discriminator threshold as a function of incident neutron angle and threshold, from the code of Cecil, et al. (Ref. 11).



2. The detector concept, with scintillating fibers placed into aluminum holders. There are six of these detector bundles, each with a phototube, placed in one collimator. There are unplugged holes exposing three of the detectors, and the other three are plugged.



3. Detector response versus incident angle of the D-T neutron source, including a 6 MeV_{ee} discriminator setting. At angles less than 10° the open holes have an efficiency much greater than the unplugged holes. At large angles, the efficiency is the same. The difference between the two is the net count rate. Also shown is the response of a bare scintillating fiber bundle, minus collimator.



4. Pulse height spectrum in the detector (with and without collimator) in the model tokamak background spectrum. Also shown for comparison is the response of a bare rod of scintillator material.